A Compact Hadron Collider at Fermilab

“Site Filler”

Pushpa Bhat and Tanaji Sen (Fermilab)

SNOWMASS Agora 2022

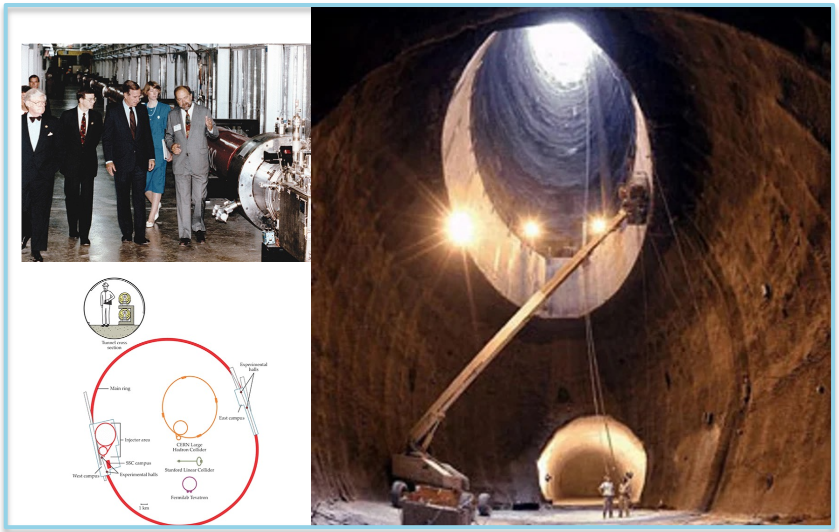
March 16 2022

Introduction

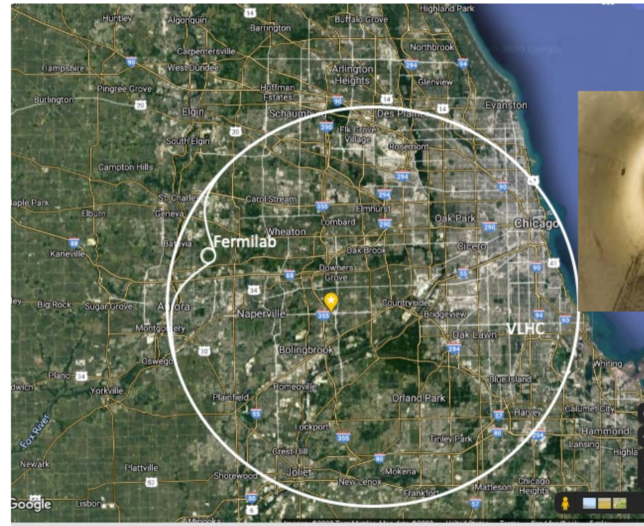
- "Very Large" colliders are grand and exciting with great physics potential
  - but timescales are too long, costs high
  - high risks of delays and uncertainties
- FCC-hh is half a century away! SppC by 2050?
- Prudent to explore intermediate, compact and cost-effective hadron collider options. Hence the site filler! ☺
  - progress in physics, extended discovery reach
  - Minimize gap in hadron collider physics
  - bolster and propagate expertise, advance technology

Previous Attempts and Studies

SSC termination was a major set-back for global HEP
~26 km tunnel and shafts constructed



VLHC233 design and R&D



100 TeV pp collider
In 100 km ring in Chicagoland

Proposed for previous Snowmass
https://arxiv.org/ftp/arxiv/papers/1306/1306.2369.pdf

Previous attempts in the US on very large machines have faltered ☹

pp “Site Filler” Collider

- A Compact Hadron Collider at Fermilab
  - Intermediate step to a larger collider; test bed for high field magnet use
  - Site filler not a new idea. Bob Wilson proposed $\sqrt{s}$=10 TeV ppbar collider in 1978. (x 2.5 ring size, x 2 with 8.6 T magnets, w.r.t. the Tevatron)

Basic Design Assumptions:

- Site, power constraints
  - 16 km Circumference; straight sections ~2.6km
  - 200 – 300 MW
- Energy 22-27 TeV
- Two IPs
  - Lumi/IP in excess of 2e34 $cm^{-2}\ s^{-1}$
  - Crossing angle in the horizontal plane at one IP and in vertical plane in the other. Separation 12 σ
  - Maximum beam-beam tune shift from all IPs 0.025
- Arc lattice
  - FODO cell length 76 m; 12 m dipoles
  - 90 deg phase advance per cell

Luminosity and beam-beam parameters

Luminosity:

$$\mathcal{L} = \frac{f_{rev} n_b N_p^2}{4\pi \sigma_x^* \sigma_y^*} R(\theta_c)$$

Beam-beam parameters:

$$\xi_x = \frac{r_p N_p \beta_x^* R(\theta_c)^2}{2\pi\gamma\sigma_x^*(\sigma_x^* + R(\theta_c)\sigma_y^*)}, \quad \xi_y = \frac{r_p N_p \beta_y^* R(\theta_c)^2}{2\pi\gamma\sigma_y^*(\sigma_x^* + R(\theta_c)\sigma_y^*)}$$

Crossing Angle factor:

$$R(\theta_c) = \frac{1}{\sqrt{1 + (\theta_c \sigma_z/(2\sigma_x^*))^2}}$$

Beam Intensity loss rate:

$$\frac{d}{dt} N_p = -n_{IP} \sigma_{tot}^{pp} \frac{\mathcal{L}}{n_b}$$

Emittance Damping:

$$\epsilon_\perp(t) = \epsilon_0 \exp[-t/\tau]$$

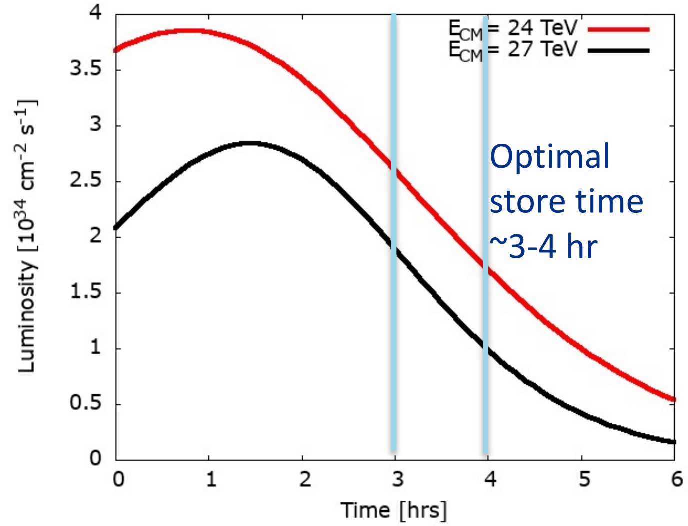
n_b=number of bunches
N_p=Number of protons/bunch
σ_x* and σ_y* are rms beam sizes,
σ_z* rms bunch length
β_x*and β_y* are lattice parameters at IP
Θ_c is crossing angle

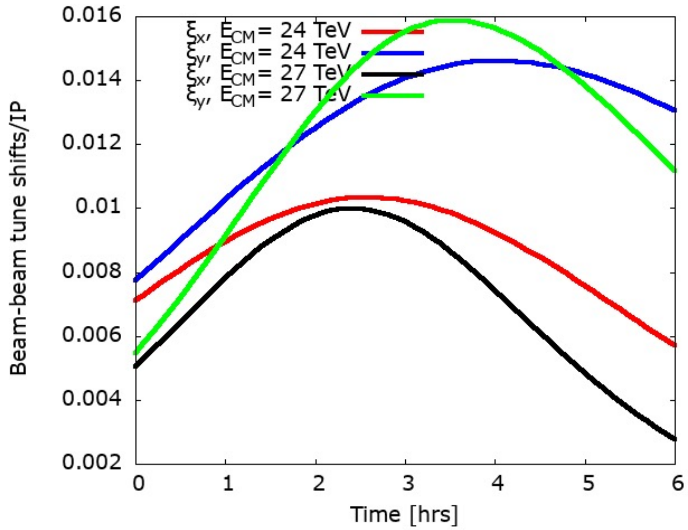
pp Site Filler

	$E_{CM} = 24$ TeV	$E_{CM} = 27$ TeV	HE-LHC	HL-LHC	FCC-hh
Circumference [km]	16	16	27	27	97.8
Beam energy [TeV]	12	13.5	13.5	7	50
Number of IPs	2	2	2	2+2	4
Main dipole field [T]	23	25.9	16	8.33	16
Number of bunches	1600	1600	2808	2808(2760)	10600
Bunch spacing [ns]	25	25	25	25	25
rms emittance $\epsilon_\perp$ [mm-mrad]	1.5	1.5	1.38	3.75(2.5)	2.2
rms bunch length σ_z [cm]	3.6	3.5	9.0	7.55(9.0)	8
β_x^*, β_y^* [m]	0.5, 0.5	0.5, 0.5	0.45 0.45	0.55 (0.15)	1.1, 1.1
Beam current [mA]	476	337	1120	580 (1120)	500
Particles/bunch N [10^{11}]	0.99	0.77	2.2	1.15 (2.2)	1.0
Beam energy [GJ]	0.30	0.24	1.4	0.36 (0.7)	
Crossing angle [μrad]	184	173	165	142(250)	104
Initial b-b tune shifts/IP (ξ_x, ξ_y)	(0.0071, 0.0077)	(0.0051, 0.0055)			0.0055
Max. b-b tune shift from 2 IPs	0.024	0.024			
Trans. emittance damping time [hrs]	1.8	1.3	3.6	25.8	1.1
Critical energy of synch. rad. [keV]	0.356	0.507			
Synch. rad. power/ beam [MW]	0.044	0.05	.1	0.005 (0.009)	2.4
Density of synch. rad in arc [W/m]	4.0	4.6	3.74		28.4
Initial $\mathcal{L}$/IP [10^{34} cm^{-2}s^{-1}]	3.7	2.1	16		5.
Peak $\mathcal{L}$/IP [10^{34} cm^{-2}s^{-1}]	3.85	2.84		1 (5 Lev)	
Number of events/crossing	92	52	460	27 (135)	170
Initial beam lifetime from burn-off [h]	6.0	7.5	2.5	40 (15)	17
Debris power into IR magnets [kW]	7.1	4.5		(4.5)	

Evolution of Luminosity and beam-beam tune shift

- Time evolution of luminosity due to beam burn-off + emittance decay from radiation damping
- Emittance growth due to IBS is not taken into account
  - ➢ increase in beam-beam tune shift is exaggerated.
- Beam-beam compensation can be deployed (e.g., electron lenses) to reduce head-on tune shifts
  - ➢ Increased luminosity





Collider Challenges

- High field dipole magnets
  - Requires fields > 20 T and high field quality
  - Magnet R&D discussed later
- Interaction region magnets
  - Must withstand debris power (4-6x that at LHC, ~HE-LHC) from pp interactions
  - Special absorber design in the IR, machine protection system
- Machine protection
  - Very high beam energy and magnetic energy
  - Improved & sophisticated collimation required
  - Photon absorbers to protect cold magnet and equipment
  - Novel diagnostics for halo control and beam loss
  - Monitor radiation damage
- High synchrotron radiation
  - ~ 10x larger than LHC but two orders of magnitude lower than FCC-hh
  - Impact on components, cryogenic system, need radiation hard electronics
  - e-cloud
- Beam dynamics issues
  - Electron cloud effects, beam-beam interactions (head-on and long-range) & compensation, beam instabilities, crab cavity operation, ….
- Cost: ???

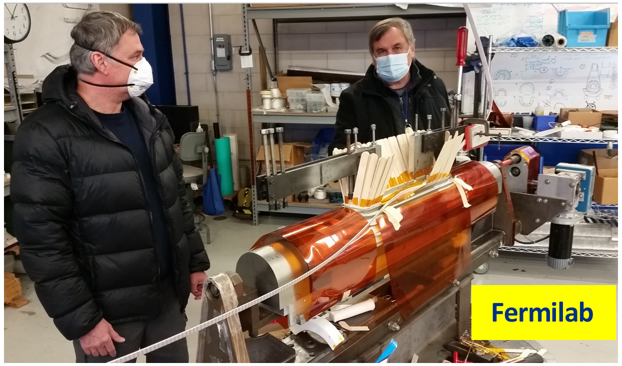
Agora: ITF Comparison Categories

	Proposal
CoM Energy and upgrades	24-27 TeV
Peak Luminosity (10^{34} cm^{-2} s^{-1})	3 - 5 $x10^{34}$ cm^{-2} s^{-1}
IP difficulties	Crab-crossing, debris power into IR magnets,…
Length of facility, km	27 km (16 km + injectors)
Length of new accelerators, km	16 km
Beam parameters challenges	Halo and beam loss control, beam-beam tune shift
Special technologies	Beam-beam compensation, crab-crossing, machine protection
R&D/validation (yrs. needed); constr. start year	High field magnets (10-15 years), ~2042,
Construction time, yrs.	7-8 years
Cost (wrt ILC) (+/-, %), level of maturity	TBD; studies, aggressive magnet R&D needed
Environment issues: AC power consumption of facility, resources (Nb, LHe…) needed	150-250 MW

Key Challenge: High Field Magnets (1)

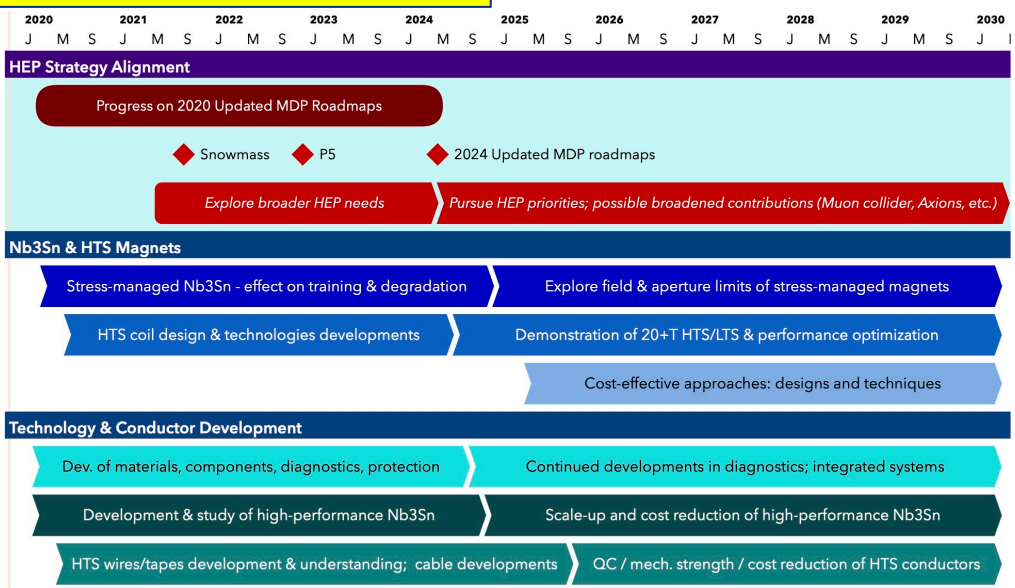
- High Field Magnet Technology
  - Current record for Nb3Sn Magnet:
    - **16.5 T on conductor, 14.5 T magnet w/ 60 mm aperture; Attempts at 17-18 T ongoing**
  - Hybrid w/ HTS insert R&D
    - Results in next 2 years: 20-25 T demo in next 10 years
  - US Magnet Development Program
    - Advance technology, improve performance, reduce cost
  - IBS research promising for >20T magnets, but early days
    - Might provide cheap, robust magnets; pursued for SPPC

R&D with advanced Technology

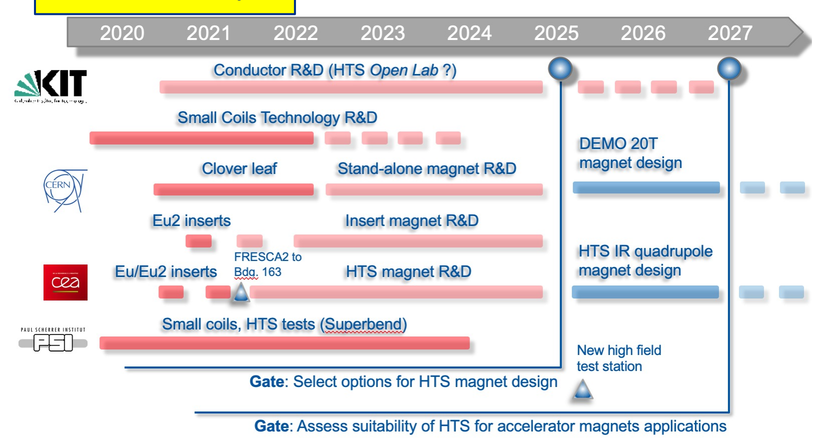


First 120-mm Nb3Sn dipole coil into SMCT structure produced by 3D printing.

US Magnet Development Program



Plan in Europe



Key Challenge: High Field Magnets (2)

nature

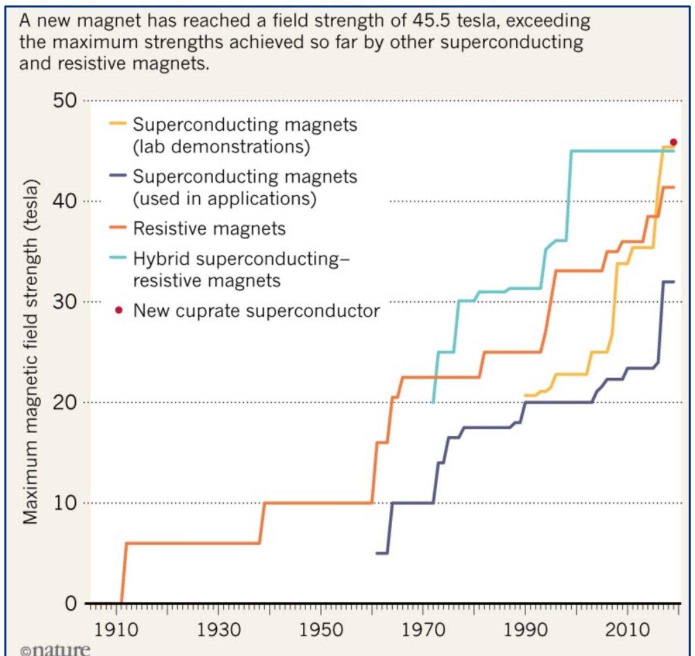
Explore content | About the journal | Publish with us | Subscribe

nature > news > article

NEWS | 12 June 2019

Superconducting magnet breaks strength world record

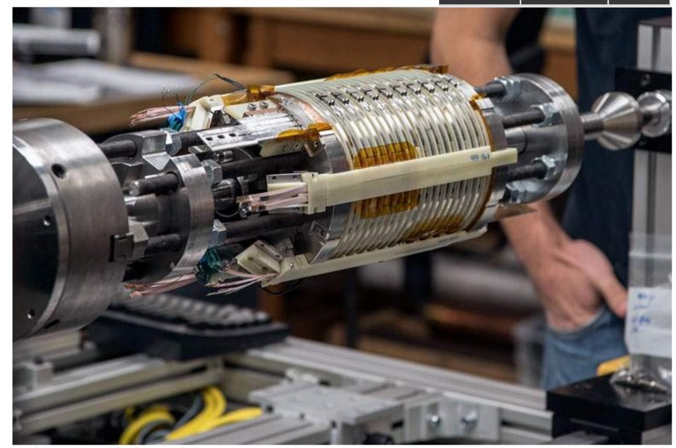
Magnet generates an unprecedented 45.5-tesla field.



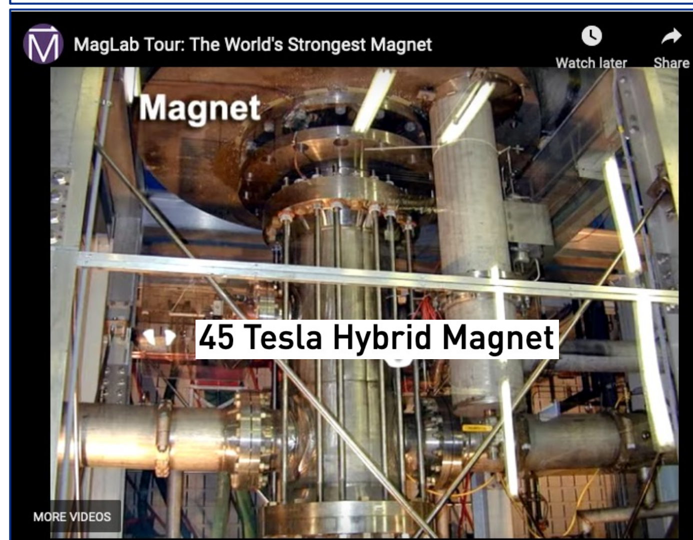
32 Tesla All-Superconducting Magnet

NATIONAL HIGH MAGNETIC FIELD LABORATORY

USER FACILITIES | USER RESOURCES | RESEARCH



The first REBCO coil for the 32 tesla magnet. Stephen Bilenky



Summary

- We have preliminary studies of a pp collider as a 16 km Fermilab site filler with collision energy in the range of 22-27 TeV.
- Luminosities 2-5e34 $cm^{-2}s^{-1}$ or higher are achievable.
- This compact collider provides an intermediate step towards a 100 TeV collider, with significant physics potential.
- Synchrotron radiation and beam dynamics issues seem manageable.
- Major challenge for the machine is the need for very high field magnets, ~22-26 T.
- Aggressive R&D on high field magnets required.

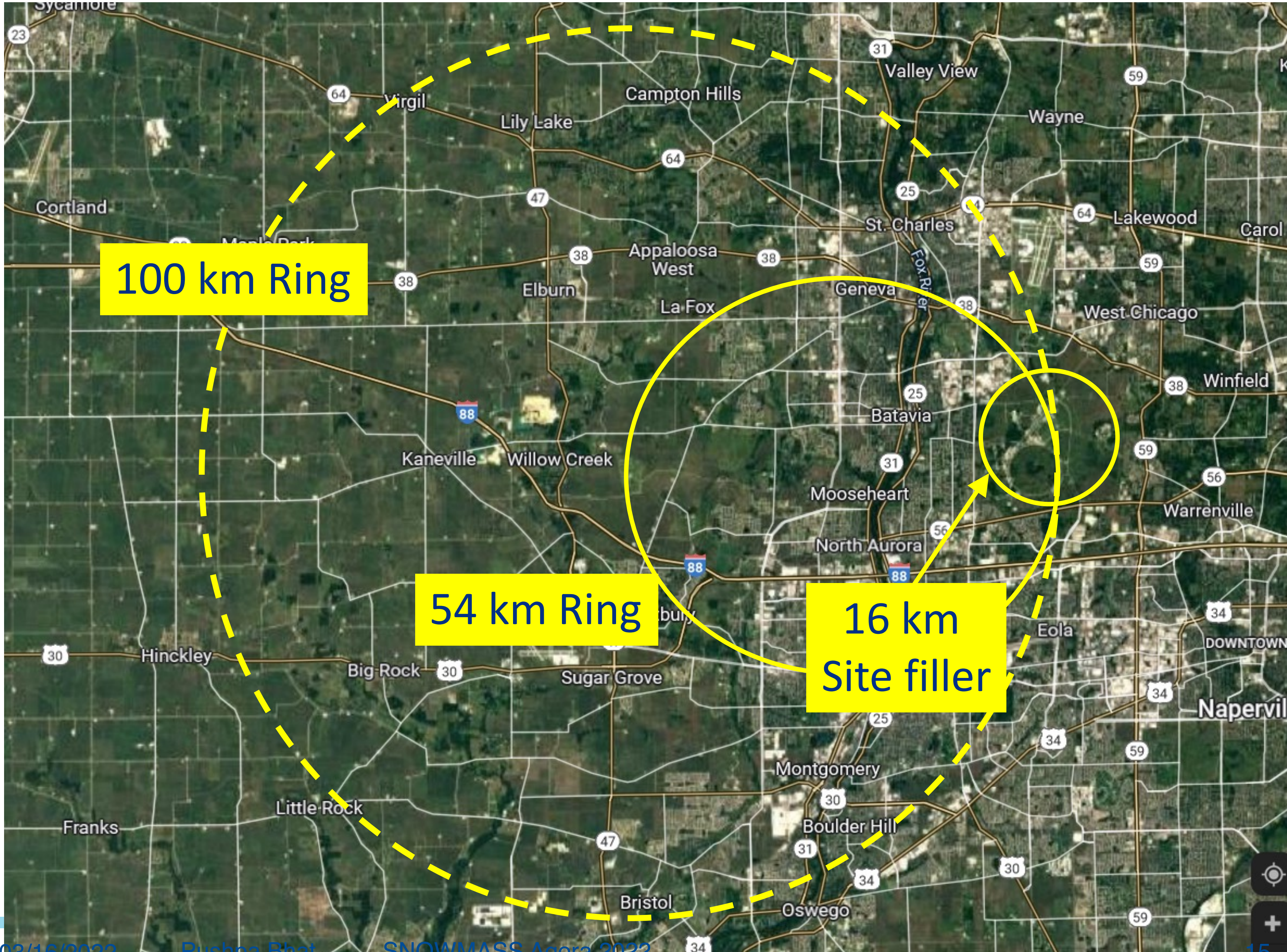
Extra Slides

Site-Filler pp Collider

FNAL-SF numbers T. Sen

parameter	FNAL SF	HE-LHC	FCC-hh	
collision energy cms [TeV]	24	27	100	
dipole field [T]	24.4	16	16	
circumference [km]	16	26.7	97.8	
beam current [A]	0.41	1.12	0.5	
bunch intensity [10^{11}]	1.05	2.2	1 (0.2)	1
bunch spacing [ns]	25	25	25 (5)	25
IP $b^*_{x,y}$ [m]	0.5, 0.5	0.45	1.1	0.3
luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	5	15	5	30
peak #events/bunch crossing	135	800	170	1020
stored energy/beam [GJ]	0.26		8.4	
synchrotron rad. [W/m/beam]	3.9	3.74	30	
transv. emit. damping time [h]	1.8		1.1	
initial proton burn off time [h]	3.5	3.0	17.0	3.4

Multi-TeV Fermilab pp Collider Options

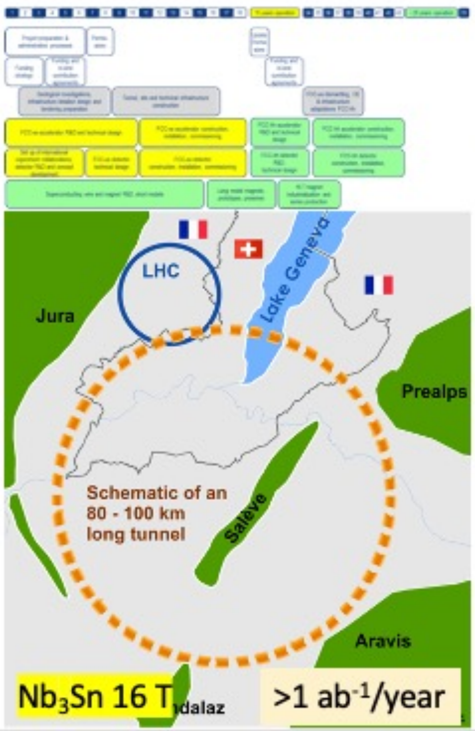


Slide from Frank Zimmermann at the Snowmass CPM 2020

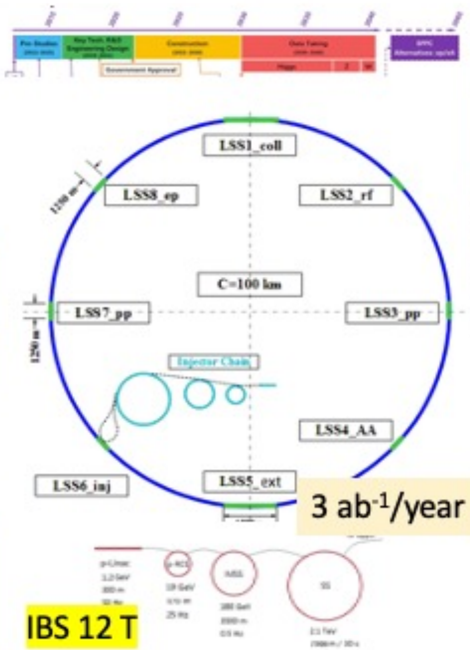
hadron colliders

LHC already has c.m. energy of 13 or 14 TeV; so I will consider only energies above LHC's; this leaves **4 contenders**

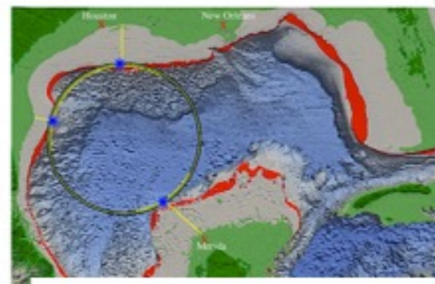
FCC-hh 100 TeV, 2^{nd} phase of FCC integrated project, collisions ~2060, *LOI 153*



SPPC 75 TeV (-150 TeV), 2^{nd} (and 3^{rd}) phase of CEPC-SPPC integrated project, collisions after 2040, *LOI 21*



Collider in the Sea 500 TeV 1900 km, as a third phase following a 300 km FCC-ee and FCC-hh in Gulf of Mexico, after 2060, *LOI 239*



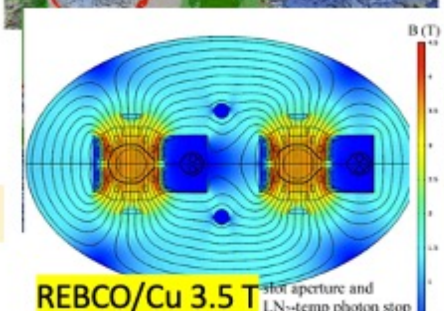
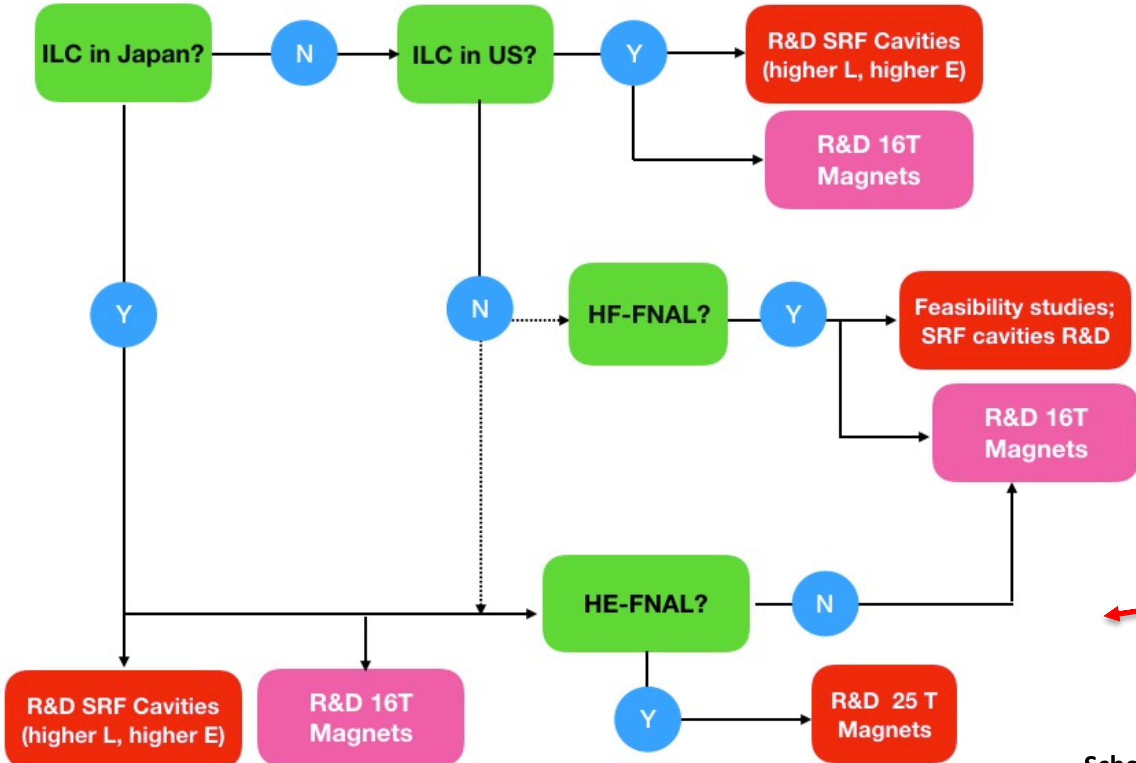


Fig. 2.3.5 T superferric dual C-dipole using NI REBCO/Cu windings.

FNAL Site Filler 24-28 TeV with 16 km circumference, collisions before 2040 (?), extendible to 233 km VLHC *LOI 237*

IBS, LTS/HTS 20-24 T

Scenarios for Colliders & R&D



ILC in Japan or US, if CERN decides on HE-LHC or FCC-hh after HL-LHC

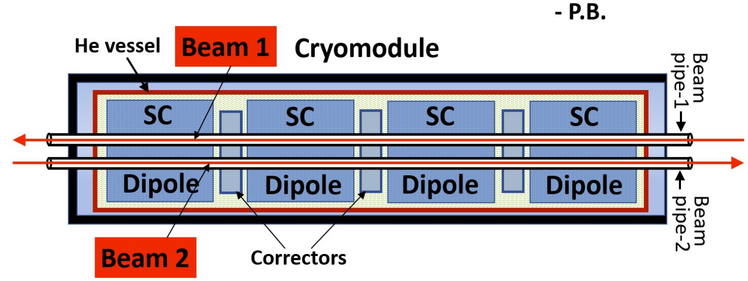
16 T magnet R&D needed for HE-LHC/FCC-hh at CERN

If CepC goes ahead, decision on US participation needs to be made

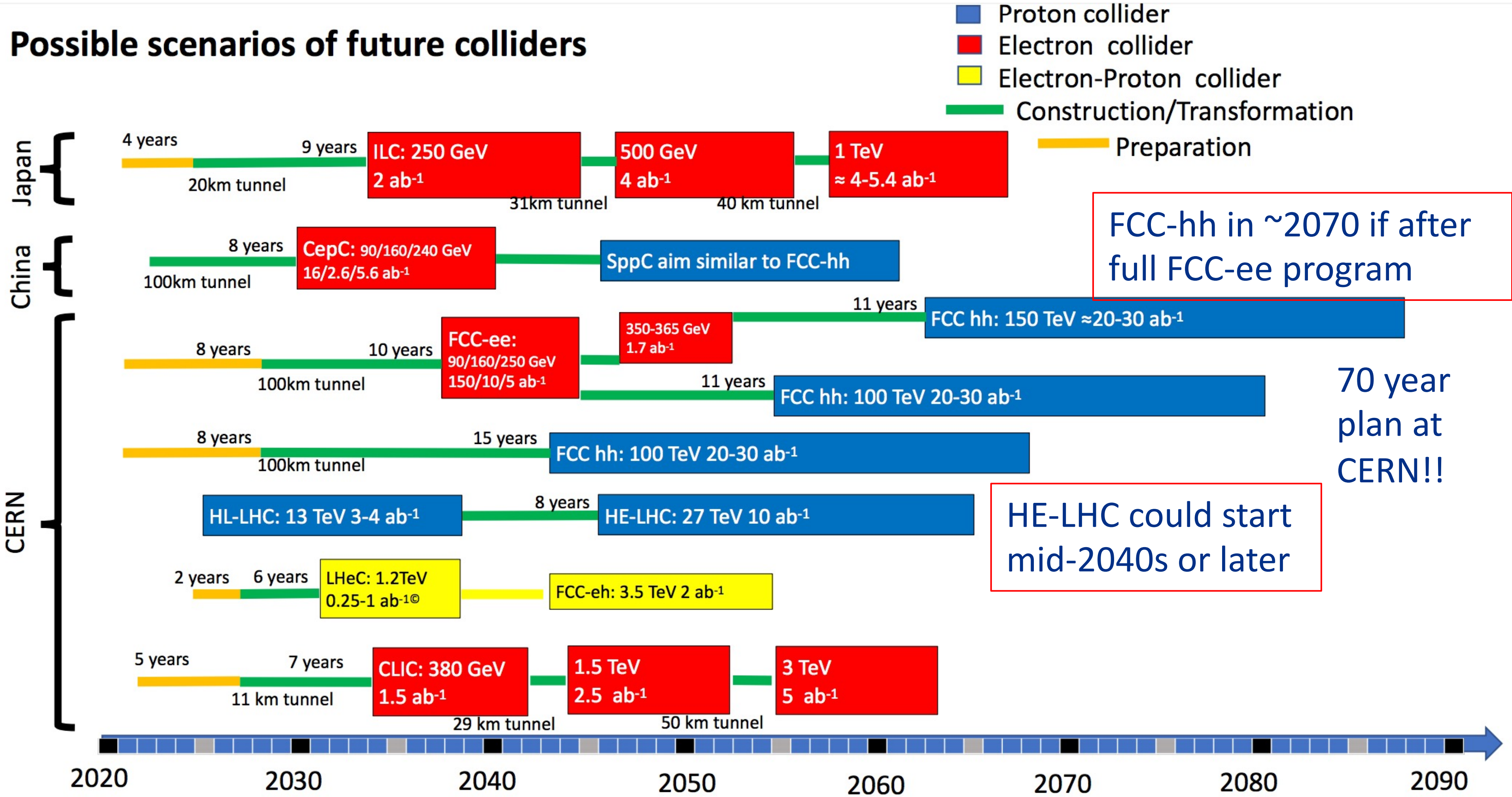
In case of no HE-LHC, and CERN proceeds with plans for FCC-ee and then FCC-hh

It is critical to start working now on reducing the timescale and costs of the future colliders!

Schematic of 25-Tesla SC Magnet Assembly
- P.B.

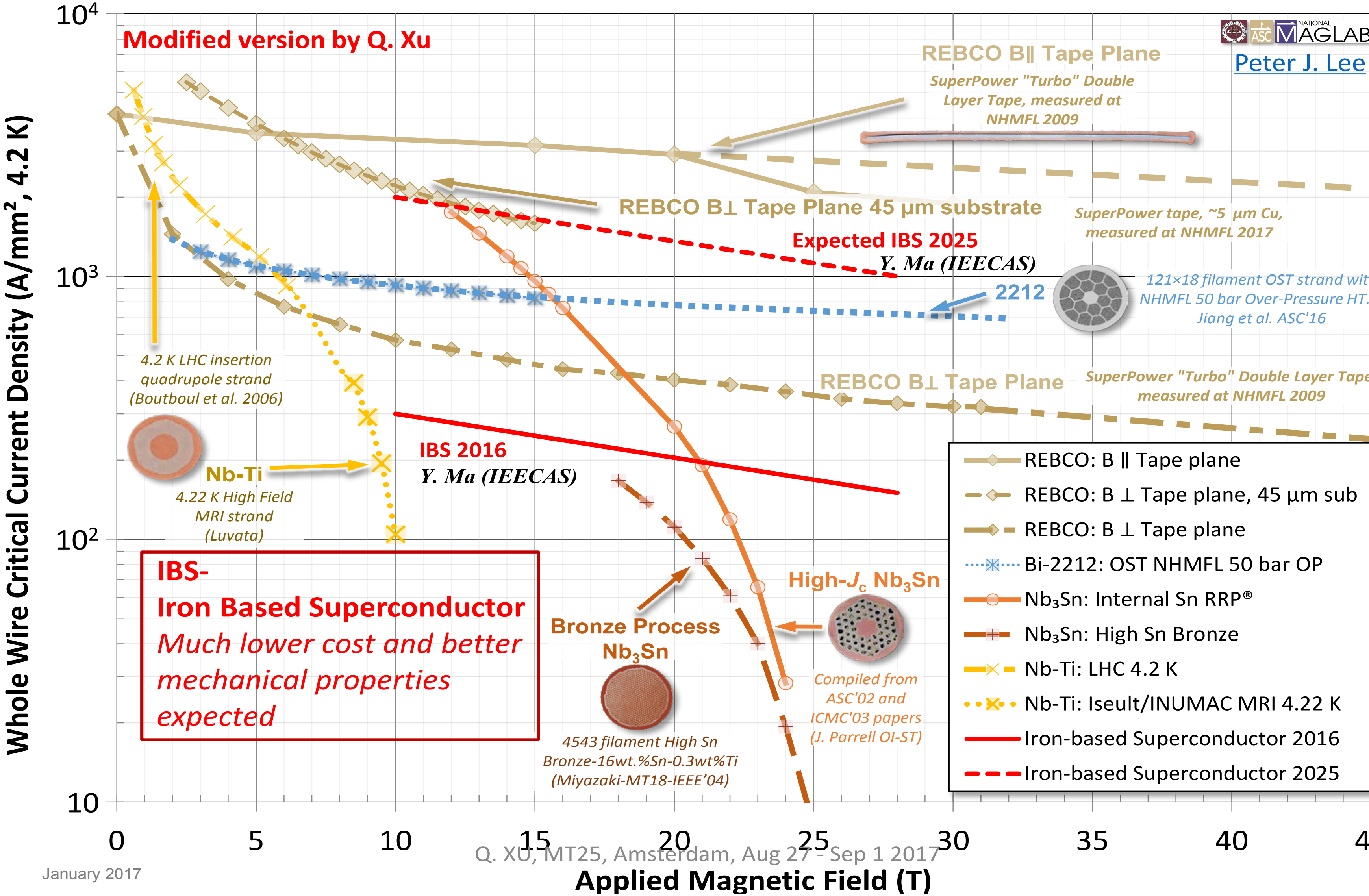


Scenarios and Timeline for Future Colliders



- HE-FNAL or HF-FNAL can probably be realized by late 2030s!

Exciting advances in HTS vs Nb_3Sn properties, but cost remains a major problem



Q. XU, MT25, Amsterdam, Aug 27 - Sep 1 2017

Comparisons

Project	Type	Energy [TeV]	Int. Lumi. [a^{-1}]	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.8 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6		149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	60 / 7000	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF

Future pp Colliders at CERN

parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	100		27	14
dipole field [T]	16		16	8.33
circumference [km]	100		27	27
straight section length [m]	1400		528	528
# IP	2 main & 2		2 & 2	2 & 2
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity [10^{11}]	1	1 (0.2)	2.2 (0.44)	(2.2) 1.15
bunch spacing [ns]	25	25 (5)	25 (5)	25
rms bunch length [cm]	7.55		7.55	(8.1) 7.55
peak luminosity [10^{34} cm^{-2}s^{-1}]	5	30	25	(5) 1
events/bunch crossing	170	1k (200)	~800 (160)	(135) 27
stored energy/beam [GJ]	8.4		1.3	(0.7) 0.36
beta* [m]	1.1-0.3		0.25	(0.20) 0.55
norm. emittance [μm]	2.2 (0.4)		2.5 (0.5)	(2.5) 3.75

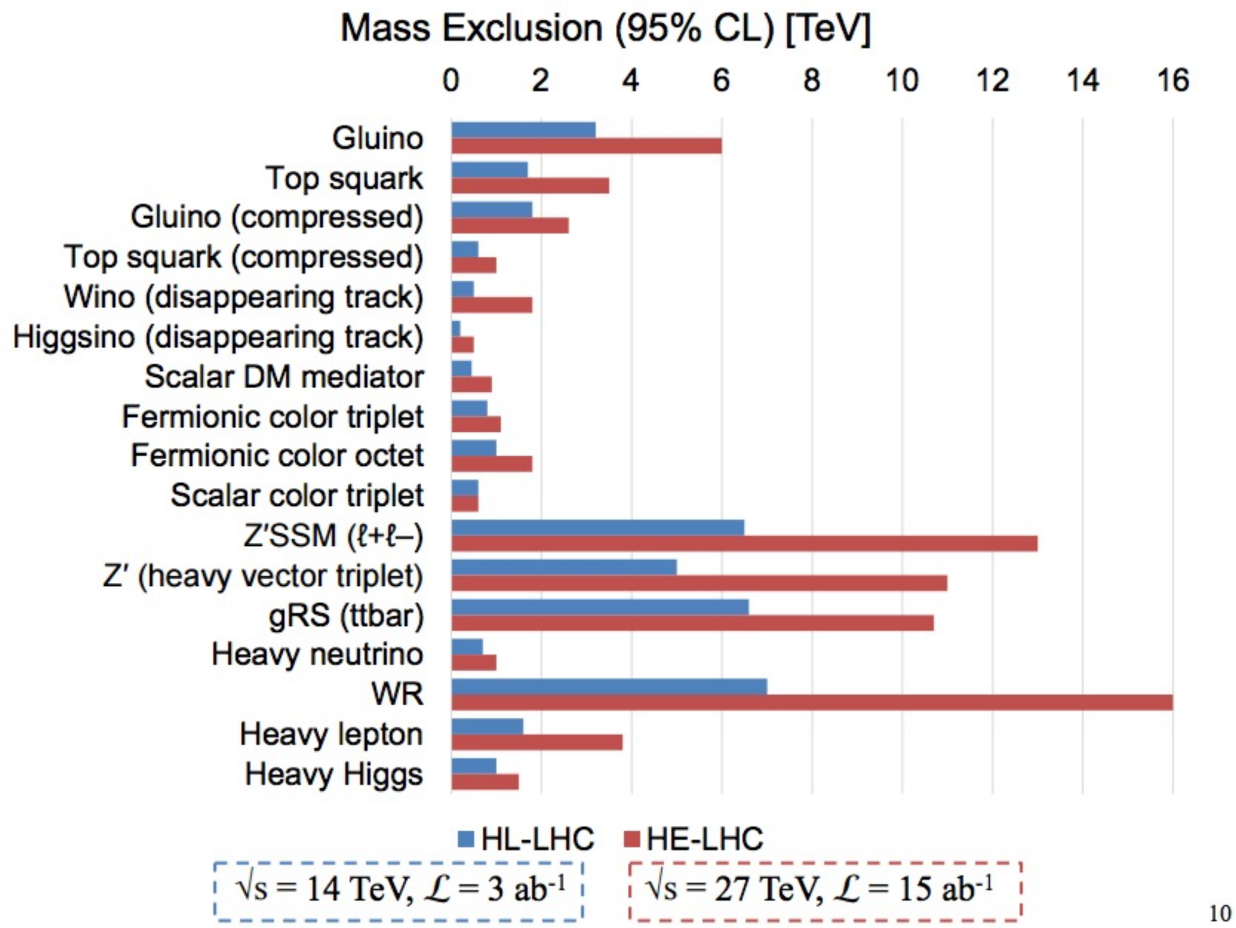
- HE-LHC and FCC-hh will be part of the European strategy 2018-2020 exercise
- Selection of “optimal” pp collisions energy is challenging

Higgs & Top Production

Process	HL-LHC ($3\ ab^{-1}$)	HE-LHC ($15\ ab^{-1}$)	ratio	HL-LHC ($1\ ab^{-1}$)	HE-LHC ($1\ ab^{-1}$)	ratio
ttbar	3.0×10^9	5.0×10^{10}	16.7	1.0×10^9	3.3×10^9	3.3
ttbar ($p_T > 2$ TeV)	3.0×10^2	1.5×10^5	500.0	1.0×10^2	1.0×10^4	100.0
t-channel	8.0×10^8	1.0×10^{10}	12.5	2.6×10^8	6.6×10^8	2.5
tW	2.0×10^8	2.0×10^9	10.0	6.6×10^7	1.3×10^8	2.0
s-channel	3.0×10^7	4.0×10^8	13.3	1.0×10^7	2.6×10^7	2.7
tqZ	3.0×10^6	6.0×10^7	20.0	1.0×10^6	4.0×10^6	4.0
ttW	3.0×10^6	4.0×10^7	13.3	1.0×10^6	2.6×10^6	2.7
ttZ	3.0×10^6	7.0×10^7	23.3	1.0×10^6	4.6×10^6	4.7
ttH	3.0×10^6	4.0×10^7	13.3	1.0×10^6	2.6×10^6	2.7
tH	3.0×10^5	6.0×10^6	20.0	1.0×10^5	4.0×10^5	4.0
tttt	5.0×10^4	2.0×10^6	40.0	1.6×10^4	1.3×10^5	8.0

Process	ggH	VBF	WH	ZH	ttH	HH
HE-LHC	2.2×10^9	1.8×10^8	5.4×10^7	3.7×10^7	4×10^7	2.1×10^6
HE/HL	13	14	13	13	23	19
HE/HL ($1\ ab^{-1}$)	2.6	2.8	2.6	2.6	4.6	3.8

BSM Physics Reach



Back to the Beginning!

Fermilab Site Filler Proposed in 1978!

1st ICFA Workshop on Possibilities and Limitations of Accelerators and Detectors

15-21 Oct 1978. Batavia, Illinois

A 10 TeV (5 on 5) ppbar site filler collider was first proposed in 1978 by Bob Wilson, Fermilab's first director

THE PENTEVAC: A SITE-FILLING ACCELERATOR AT FERMILAB

R. R. Wilson

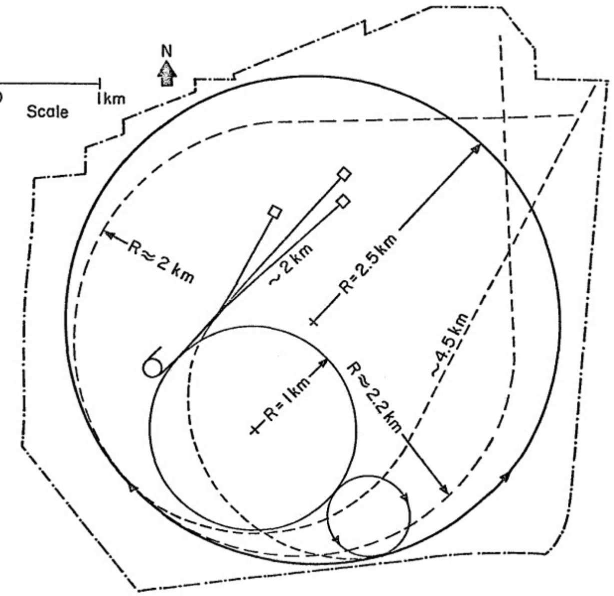
(b) 5 TeV Antiprotons on 5 TeV Protons

By the time the Pentevac in constructed, we can assume that techniques for cooling antiprotons will have been developed and will have been used for colliding beam experiments in the Tevatron. These beams could be transferred directly to the Pentevac ring for slow acceleration to 5 TeV each. Thus we can contemplate the exciting prospect of reaching a center-of-mass energy of 10 TeV in colliding beam experiments in the Pentevac. There

w.r.t. Tevatron

x 2.5 ring size

x 2 with 8.6 T magnets



Later in
Fantasies of future Fermilab facilities
R. R. Wilson
Rev. Mod. Phys. 51, 259 – Published 1 April 1979

Bjorken (B.J.) proposed it at the 15th annual Users' meeting in 1983 and that it could be completed by 1990